STABILITY BOUNDARY OF ION BEAMS IN THE FAIR STORAGE RINGS

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Abstract

The FAIR Storage Rings (CR, RESR and NESR) are designed for efficient cooling, accumulation, deceleration and performing nuclear physics experiments with antiproton and rare isotopes beams. Tracking studies for all these rings have been performed to estimate the dynamic aperture and other properties of beam stability. The sextupole strength limits have to be determined in order to provide a reasonable estimate of the stability boundary and the needed correction. We report on quantitative studies of the effects of sextupole magnets and multipoles on the dynamic aperture of the rings, and show that the all these non linear field components in the present magnet designs are unlikely to impose a severe limitation.

INTRODUCTION

The storage rings of the FAIR project [1] have different tasks and to reach the desired beam stability one has to consider its dependence on the particular lattice design [2-5]. In Table 1 some parameters of the rings are given. For the CR we consider only the optical mode for antiproton operation.

Table 1: Parameters of the Storage Rings

Parameters	CR	RESR	NESR
Circumference, C, m	216.25	239.9	222.8
Max. rigidity , Tm	13	13	13
Transition energy, $\gamma_{tr,}$	3.7	6.4	4.6
Tune Q_x/Q_y	4.26 / 4.84	3.12/4.1	4.20 /1.87
Trans. acceptance (mm mrad)	240	25/25	150/40
Mom. acceptance	6%	2%	3%

The study of a particle motion in phase space by particle tracking can give significant insight into the dynamics of a single particle. The dynamic aperture tells us about the maximal stable area in the rings depending on different kinds of non-linear imperfections of the magnets. For the proper operation of the storage rings we also need to know not only the overall stability of the particle beam, but one needs to know the particle behaviour within the required beam acceptance. Usually in each ring we have to use nonlinear optical elements (such as sextupole, octupole magnets) for the correction of different kinds of aberrations. The particles with simultaneously large horizontal and vertical betatron amplitudes have coupled motion which leads to beating of the phase space (which we call filamentation effect) and consequently to a large particle amplitude, that can provoke an encounter with the wall.

To study the particle motion in the rings we use the DYNAMO code, which provides a tool for study of the stability boundary by providing the information about the particle amplitudes. In the code the invariant J for each particle is calculated turn by turn. The invariant J is identical to the Courant-Snyder invariant and expresses the invariance of the particle motion in normalized phase-space. In a linear lattice a particle follows a circle in action angle phase space with a radius equal to the action J_0 (Fig. 1).

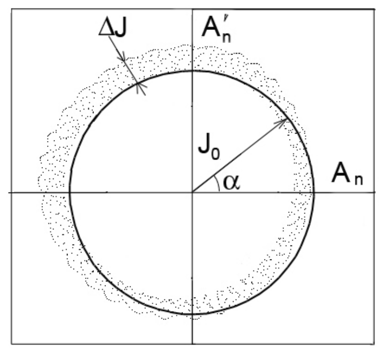

Figure 1: Filamentation of phase space.

The nonlinear field appearance along the particle trajectory brings an amplitude variation ΔJ to the action which is in the case of a single sextupole magnet proportional to the particle amplitude and calculated by formulae:

$$\Delta J_x = \frac{1}{2} X'_n \sqrt{\beta_x} \frac{1}{B\rho} \frac{\partial^2 B}{\partial x^2} L_{eff} \left(x^2 - y^2\right) \quad (1)$$

$$\Delta J_y = \frac{1}{2} Y'_n \sqrt{\beta_y} \frac{1}{B\rho} \frac{\partial^2 B}{\partial x^2} L_{eff}\, xy \quad (2)$$

(β - betatron function, X_n, Y_n - normalized coordinates, $B\rho$ - rigidity, L_{eff} – effective length of sextupole magnets).

In Fig. 1 one can see as an example the ΔJ in the horizontal plane calculated numerically for the CR, where 24 sextupoele magnets are used.

The invariants formalism allows us to study the evolution of the beam filamentation and cutting the ring acceptance. In the following section we present the growth of the action obtained for each of the storage rings by summing over 1000 turns and all sextupoles, which are installed in the rings. The observation of the evolution of the action coordinates over many turns allows us to identify the expected particle loss and loss of beam stability if there is no compensation. We call the boundary stability the area, within which there is no particle loss taking into account the aperture of all magnets and insertions devices.

THE COLLECTOR RING (CR)

The CR will be used for fast cooling of the hot beams coming from separators. From a beam dynamics perspective the major effects limiting the ring's performance are chromatic effects of large aperture quadrupole magnets. In the CR the sophistication of chromaticity correction is limited because of the lack of the free space in the arcs. There are 24 sextupole magnets placed in the arcs in high dispersion areas. These sextupoles can cause a number of different destabilizing effects, which are driven by only a few third order resonances. Fortunately in the CR the chromaticity is not high and some of the higher order aberrations are very small and need not to be compensated. For example the amplitude dependent tune shift is negligible.

The CR lattice has two long straight sections for the installation of RF cavities for bunch rotation, the stochastic cooling system, injection-extraction kickers and septum magnets. There is a large disparity between the aperture requirements in the long straight section where dispersion is zero and in arcs where it reaches 5 m. This difference represents 25 cm of extra aperture for wide aperture quadrupoles. In one of the long straight sections the quadrupole aperture requirement is similar to what we have in the arcs in order to perform injection and extraction of a beam. The second straight section can be designed with much smaller aperture of magnets. The CR described in ref. [3] has two identical long straight sections and the lattice structure has two Super Periods (SP2). The dynamic aperture of the CR with SP2 has been calculated and given in ref. [3]. We consider also the CR lattice with narrow quadrupoles placed in one of the straight sections, where there is no large aperture requirement. Due to the fact that narrow and wide quadrupole magnets have different errors of the magnetic field, the CR lattice has Super Period One (SP1) with respect to the distribution of the systematic field errors in the lattice. For the lattice with SP1 the present distribution of sextupoles in the arcs causes a strong filamentation effect. In Fig. 2 the minimal and maximal action variables $J_{x,y}$ as a function of the initial horizontal and the vertical amplitudes (corresponding to the radius R at the angle α as in Fig. 4) are shown. The invariants $J_{0x,y}$ correspond to the theoretical beam emittance at the radius R in the linear lattice. One can see that the filamentation effect is strong in both planes. According to the Monte-Carlo calculation this filamentation effect leads to 40% beam loss. The amplitude variation ΔJ is minimized if we insert two additional harmonic sextupole magnets in the middle of the straight section with narrow aperture quadupoles. In Fig. 3 the action variable after correction with harmonic sextupoles including nonlinear field errors of all magnets are plotted. One can see that the filamentation is not completely canceled especially for large particle amplitudes in the horizontal plane. This causes some reduction of the stability boundary. In Fig.4 the calculated limit of the particle survival in the CR is shown. One can see that the boundary stability is smaller than the theoretical beam boundary especially for off momentum particles. The expected beam loss is about 7-15% depending on the particle distribution. The beam loss is caused mainly by the particles stopped on the real aperture of the insertion devices (RF cavities, stochastic cooling system).

A number of numerical simulations indicates that the stability boundary does not depend on the strength of the high order multipoles or on the choice of the linear tunes Q_x and Q_y. This leads to the suggestions that the stability boundary of the CR lattice is insensitive to the magnitude of the higher multipoles and the linear tune needs to be chosen to avoid the resonances driven by the lower order multipoles.

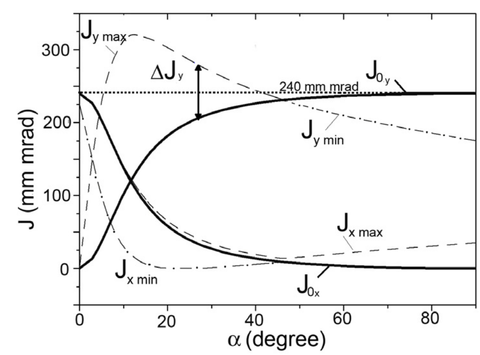

Figure 2: Action variables without harmonic sextupole correction. Δp/p=0.

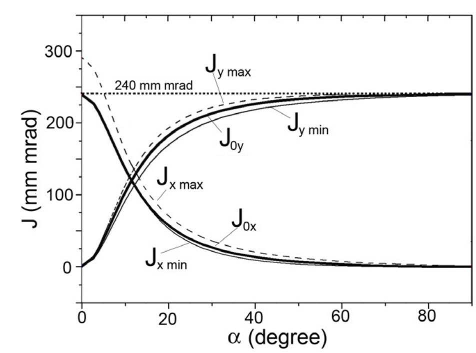

Figure 3: Action variables after correction with harmonic sextupole. Δp/p=0.

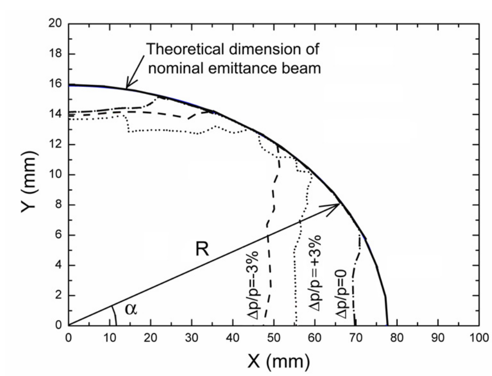

Figure 4: Limit of beam survival with real aperture limits.

THE RESR

The RESR lattice [3, 4] has been designed with emphasis on a high accumulation rate by stochastic cooling. The injection/extraction and accumulation of the antiproton beam are performed on orbits with momentum offsets of -0.8% and +0.8 % respectively, which means that particles have a large amplitude in the sextupole magnets (up to 15 cm). 8 sextupole magnets are planned to be used for the chromaticity correction. Obviously these sextupole magnets produce a filamentation effect, which increases the beam boundary and consequently the boundary stability is reduced. The required acceptance of the RESR is 25 mm mrad in both planes. In Fig. 5 the action variables and their variation depending on the particle amplitudes are shown. The action variable J_0 corresponds to the ring acceptance of 25 mm mrad. For large amplitudes one observes an increasing amplitude variation ΔJ leading eventually to the reduction of the boundary stability by about 3 mm mrad.

Introduction in the numerical simulations of systematic errors of the magnetic filed does not give a significant contribution to the reduction of the boundary stability. Simulations show that the additional amplitude variation is less than 0.5 mm mrad.

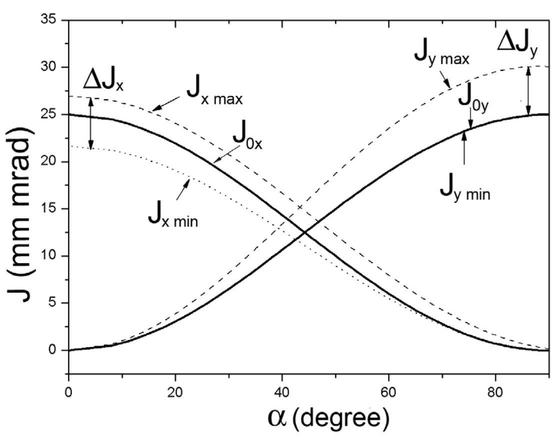

Figure 5: Action variables in the RESR for the accumulation orbit with $\Delta p/p$=+0.8%.

THE NESR

The NESR has been designed to have two operational modes. One of them is the standard mode which is dedicated to the experimental program with stored stable and radioactive ion beams and to the preparation of low energy antiprotons coming from the RESR. Another one is the mode for performing of the ion beam collision with an electron beam. Due to a larger aperture of magnets a maximum horizontal acceptance can be reached 150 mm mrad and 40 mm mrad in vertical plane, while the momentum acceptance is ±1.5%. To achieve an optimal chromaticity correction the arcs of the NESR lattice have been essentially modified compared to the lattice given in ref.[5]. The sextupole position in the arcs is chosen such that driving terms for half and third integer resonances are minimized. Now 12 sextupole magnets are used to minimize the chromaticity.

In the collision mode the NESR optics is different compare to the standard mode. We have a sensitive section just adjacent to the collision point. To maximize the luminosity the optics is calculated to produce small values of betatron functions at the collision point and consequently large values in the adjacent quadrupoles. For this mode the sextupole distribution causes a filamentation effect leading to some emittance blow up. In Fig. 6 the amplitude variation depending on the beam emittance for the colliding mode is shown. We see that the emittance blow up is about 20%, which in principle does not limit the boundary stability of the ring. Additionally powerful beam cooling will be applied and the amplitude variation will be even further reduced to negligible values.

Tracking studies including all nonlinear field errors and their influence on the filamentation have to be done in the further steps of the NESR optics optimization.

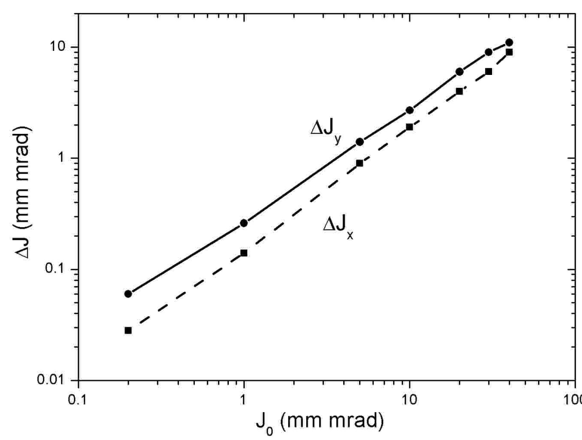

Figure 6: Variation of action amplitude versus beam emittance.

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